Simulating the formation of Hurricane Isabel (2003) with AIRS data

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[1] Using the AIRS retrieved temperature and humidity profiles, the Saharan Air Layer (SAL) influence on the formation of Hurricane Isabel (2003) is simulated numerically with the MM5 model. The warmth and dryness of the SAL (the thermodynamic effect) is assimilated by use of the nudging technique, which enables the model thermodynamic state to be relaxed to the profiles of the AIRS retrieved data for the regions without cloud contamination. By incorporating the AIRS data, MM5 better simulates the large-scale flow patterns and the timing and location of the formation of Hurricane Isabel and its subsequent track. By comparing with an experiment without nudging of the AIRS data, it is shown that the SAL may have delayed the formation of Hurricane Isabel and inhibited the development of another tropical disturbance to the east. This case study confirms the argument by Dunion and Velden (2004) that the SAL can suppress Atlantic tropical cyclone activity by increasing the vertical wind shear, reducing the mean relative humidity, and stabilizing the environment at lower levels. **Citation:** Wu, L., S. A. Braun, J. J. Qu, and X. Hao (2006), Simulating the formation of Hurricane Isabel (2003) with AIRS data, *Geophys. Res. Lett.*, *33*, L04804, doi:10.1029/2005GL024665.

1. Introduction

[2] During boreal summer months, as air moves across the vast Sahara Desert, it becomes warm and dry, forming a deep mixed layer in the troposphere [*Carlson and Prospero*, 1972]. The elevated mixed layer, called the Saharan Air Layer (SAL), extends well westward into the tropical Atlantic and contains a substantial amount of mineral dust. The layer of dusty, dry and warm air extends to as far as the western Caribbean Sea [*Dunion and Velden*, 2004], usually between 10° and 30°N. Its base starts at about 500 m just off the North African coast and rises westward and southward to about 700 hPa [*Diaz et al.*, 1976; *Karyampudi and Carlson*, 1988]. Previous studies suggested that a strong SAL could aid wave growth and tropical cyclone development by supporting convection along its leading and southern borders [*Karyampudi and Carlson*, 1988; *Karyampudi and Pierce*, 2002].

[3] Recently, using Geostationary Operational Environmental Satellite (GOES) data, *Dunion and Velden* [2004] developed a new method for tracking the SAL and examined the effects of the SAL on tropical cyclone activity. They suggested that the SAL might play a major role in suppressing Atlantic tropical cyclone activity. Numerical models such as the Pennsylvania State University-National Center for Atmospheric Research fifth-generation, nonhydrostatic mesoscale model (MM5) have occasionally successfully simulated the formation of tropical cyclones [e.g., *Braun and Tao*, 2000; *Davis and Bosart*, 2001; *Wu et al.*, 2006], but the SAL effect has not been demonstrated numerically because limited observational data in the SAL are available for model initializations.

[4] After the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU), and the microwave Humidity Sounder of Brazil (HSB) were launched with the NASA Aqua satellite in 2002, new data products retrieved from the AIRS suite became available for studying the effects of the warm, dry air mass associated with the SAL (referred to as the thermodynamic effect hereafter). The vertical profiles of the retrieved temperature and humidity provide an unprecedented opportunity to examine the thermodynamic effect of the SAL by allowing the model thermodynamic state to be relaxed to the observational state in the regions without cloud contamination. The objective of this paper is to numerically demonstrate the thermodynamic effect of the SAL on the formation of Hurricane Isabel (2003).

2. AIRS Data Description

[5] AIRS, AMSU and HSB consist of an innovative atmospheric sounding group of visible, infrared, and microwave sensors. AIRS has 2378 spectral channels including the important temperature sounding regions in the 4.2 and 15 μm CO_2 bands, water vapor sounding in the 6.3 μm water vapor band, and ozone sounding in the 9.6 μm region [*Chahine et al.*, 2001]. The AMSU and HSB instruments are composed of two cross-track scanning multi-spectral microwave radiometers. A cloud-clearing technique is used to retrieve the temperature sounding of partly cloudy atmospheres [*Aumann and Chahine*, 1976]. The standard AIRS retrieved profiles of temperature and humidity (Level 2 products) are obtained twice daily (day and night) on a 1:30 p.m. sun synchronous orbit from a 705-km altitude with a horizontal resolution of ~50 km and 28 pressure levels.

3. The SAL During the Formation of Hurricane Isabel

[6] Hurricane Isabel originated from a tropical wave near the western coast of Africa on 1 September 2003 [*Beven and Cobb*, 2004]. A tropical depression centered at 13.8°N, 31.4°W formed at 0000 UTC 6 September. It became

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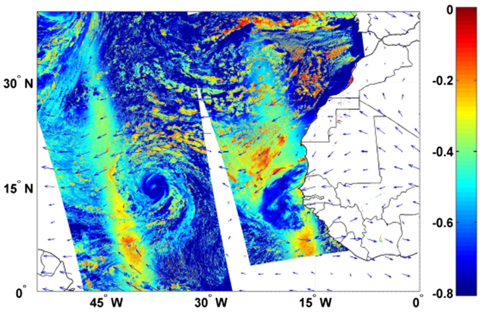

Figure 1. The derived NDDI image superimposed with NCEP 12Z 850 hPa wind field, showing Hurricane Isabel and the tropical disturbance near the western African coast in the dusty environment on September 7. There are false dust signals associated with the sun glint and stratocumulus.

Tropical Storm Isabel six hours later and intensified into a hurricane at 1200 UTC 7 September. Based upon the sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) solar reflective bands to sand and dust, a Normalized Difference Dust Index (NDDI) is defined for detecting the suspended sand and dust (J. Qu et al., Asian dust storm monitoring from space using MODIS RSB measurements, submitted to *IEEE Geoscience and Remote Sensing Letters*, 2006) (Figure 1). Heavy dust areas over ocean are generally indicated by larger NDDI values. The presence of deep clouds can obscure the detection of dust that is below 500 hPa because the infrared sensor cannot detect the thermal emissions through thick cloud layers, resulting in low NDDI values. Low clouds and sun glint can produce large values. Figure 1 shows the well-developed eye of Isabel near 38°W and a new convective cloud system just off the African coast. A heavy dust storm associated with strong easterly flow intrudes into the Atlantic Ocean from western Africa between 15° and 30°N, but the dust becomes diffuse and difficult to detect further westward away from the African coast.

[7] The dry, warm air associated with the SAL can be identified from the AIRS data products. Figure 2 shows the AIRS potential temperature and relative humidity fields on September 1 (Figures 2a and 2b) and 7 (Figures 2c and 2d). In this case no data are used over land. The SAL is clearly indicated by the relatively high potential temperature (>314 K) and low relative humidity in the region off the western African coast. As identified by relatively high potential temperature (∼312 K), the SAL potentially extends westward as far as Caribbean Sea. This finding is consistent with the examples from the GOES satellite imagery given by *Dunion and Velden* [2004]. As shown in Figures 2c and 2d, the 700 hPa relative humidity values of 25–45% are similar to values from composite SAL soundings that were shown by *Dunion and Velden* [2004], indicating that the AIRS products can capture the presence of the SAL. When Isabel appeared as a tropical disturbance on September 1, it was located at about 10°N, 20°W, nearly on the southern boundary of the warmest portion of the SAL (Figures 2a and 2b). The disturbance intensified into a tropical storm after its center (15°N, 40°W) moved away from this part of the SAL (Figures 2c and 2d).

4. The Simulated SAL Influence

[8] To understand the SAL influence on the formation of Isabel, numerical simulations are conducted from 1 to 12 September 2003. The integration period includes the formation and intensification of Hurricane Isabel (Isabel reached its peak intensity of 145 knots on 11 September) and the evolution of a tropical disturbance to the east (Figure 1) that failed to develop into a named tropical cyclone. A single domain is used consisting of 226 × 481 grid points with a 21-km spacing covering an area from 1.7°S to 37.5°N and 89.5°W to 0.9°E. There are 28 vertical levels with higher resolution in the planetary boundary layer (PBL). In the present simulations, the coarse (2.5°×2.5° resolution) 12-hourly re-analyses of the National Centers for Environmental Prediction (NECP) are used to provide initial and boundary conditions. No bogus vortex is included in the initial conditions. Model physics options include the Betts-Miller cumulus parameterization, the warm rain scheme, the Medium-Range Forecast (MRF) PBL scheme, and the CCM2 radiation scheme.

[9] In the control experiment, the thermodynamic effect of the SAL is assimilated through the nudging technique, which forces the model state to be relaxed toward the observations by adding a Newtonian relaxation term in a prognostic equation [*Stauffer and Seaman*, 1990]. In this study, AIRS retrieved temperature and humidity profiles are used as the observations in the areas lacking deep convective activity. The nudging is conducted continually through the integration period including both daytime and nighttime data. For comparison, a second experiment is conducted using the same model setup but without the observational nudging. In this case, information on the SAL is included only through the initial and lateral boundary conditions derived from the NCEP reanalysis.

[10] In the control experiment, the timing and location of formation and the subsequent track of Hurricane Isabel are well simulated (Figure 3a). The simulated tropical cyclone formed at 0600 UTC September 5, one day earlier than observed. The formation location is at 13.5°N, 30.9°W,

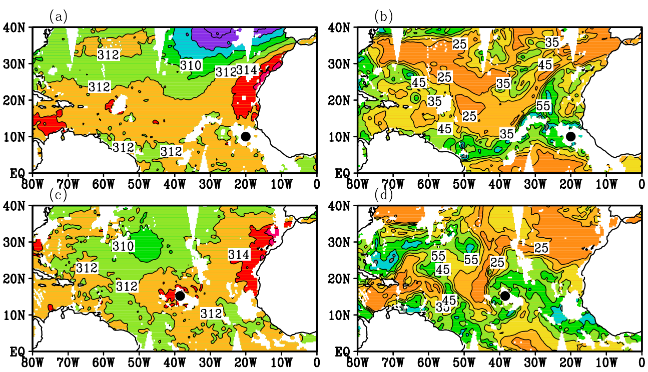

Figure 2. (a and c) 700 hPa potential temperature and (b and d) relative humidity from AIRS for September 1 (Figures 1a and 1b) and September 7 (Figures 1c and 1d). The solid dots indicate the center of Hurricane Isabel and the associated tropical disturbance.

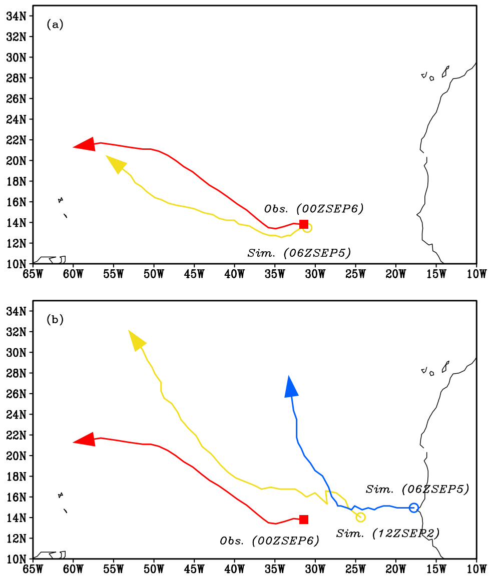

Figure 3. Comparisons of the observed Isabel track (red) with the simulated tropical cyclone tracks in the numerical experiments (a) with nudging the AIRS data and (b) without. The formation time is indicated for Isabel and the simulated tropical cyclones.

which is comparable to the observed one at 13.9°N, 32.7°W. The simulated tropical cyclone moves slightly slower than the observed storm. Based upon the maximum wind at the lowest model level (38 m), the simulated tropical cyclone reaches hurricane strength at 1800 UTC September 6, also one day earlier than observed. Furthermore, the model fails to simulate the deepening of the central pressure after September 8, in part due to the relatively coarse resolution. In the experiment without nudging of the AIRS data, on the other hand, the simulated tropical cyclone evolution is dramatically different than the observations. As shown in Figure 3b, the simulated tropical disturbance associated with Isabel becomes a tropical storm at 1200 UTC September 2, four days earlier than observed. The simulated storm takes a track different from Isabel by moving to its north. An additional tropical cyclone forms just off the western coast of Africa. These two experiments clearly demonstrate that the effect of the SAL delayed the formation of Hurricane Isabel and inhibited the development of the other tropical disturbance to the east. The simulation results also suggest that the nudging technique reasonably incorporates the SAL effect in the simulation.

[11] Although the SAL effect is to some extent represented in the initial and lateral boundary conditions in the case without nudging of AIRS data, the subsequent evolution of the SAL effect may be poorly represented due to a lack of the relevant model physics. One reason is that the presence of the SAL mineral dust can affect the thermodynamic state through radiative heating [*Carlson and Benjamin*, 1980] and likely through modifying cloud processes by serving as cloud condensation nuclei (CCN) or ice nuclei [*van den Heever et al.*, 2005]. These effects are considered indirectly through the corrections of the nudging technique.

[12] To examine the impacts of the AIRS data, we examine the horizontal wind, relative humidity, and temperature, which are averaged over a box covering 10–20°N, 15–30°W and over the period September 1–7. The selected region and period cover the formation locations and processes of the simulated tropical cyclones (Figure 3). Averaging over a large area and over a long time period obviously smoothes out the differences between the experiments with and without nudging, but serves to highlight important impacts on the storm's environmental conditions. The nudging significantly reduces the mean relative humidity throughout the troposphere except in the lowest 1–1.5 km since the SAL base is at about 850 hPa (Figure 4a). The simulated mean relative humidity is about 68% at 1.5 km and about 63% at 3 km, which is comparable to *Jordan*'s [1958] mean tropical sounding with the humidity of about 74% at 850 hPa and about 57% at 700 hPa. The relative humidity at about 6 km is about 20% lower in the control experiment. The decrease in relative humidity can suppress the formation of tropical cyclones [*Gray*, 1968]. *Dunion and Velden* [2004] suggested that the dry air associated with the SAL could disrupt a tropical cyclone by enhancing convectively driven downdrafts. Figure 4b shows the difference in temperature between the control run and the experiment without nudging of AIRS data. Positive temperature anomalies extend from the top of the boundary layer to 5 km, indicating that the relatively warm air associated with the SAL is better represented in the nudging

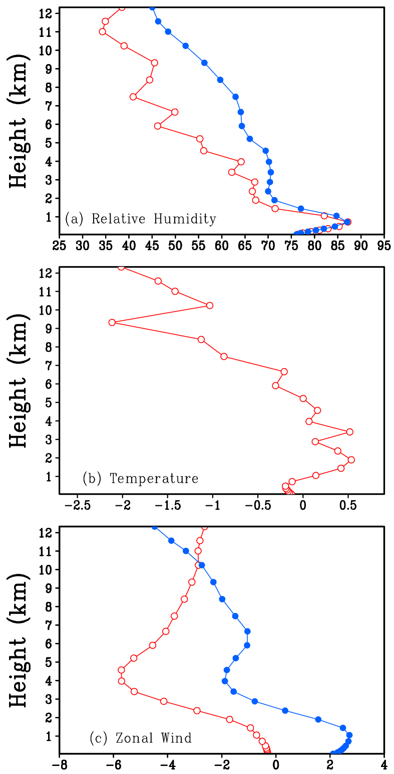

Figure 4. Simulated profiles of (a) relative humidity (%), (b) temperature difference (K) between the nudging and non-nudging numerical experiments, and (c) zonal wind (ms-1). The open and solid dots in Figures 4a and 4c denote the experiments with and without nudging the AIRS data, respectively. The derived profiles are averaged over the period of September 1–7 and over the region of 10–20°N, 15–30°W.

experiment. As a result, the SAL stabilizes the environmental air at lower levels, leading to a suppression of convective activity and thus tropical cyclone formation. In the nudging experiment, a latitude-height cross section of the zonal wind averaged over 15–40°W (figure not shown) indicates that the SAL is associated with an easterly wind maximum of about 10 m s^{-1} around 18°N at a height of 4 km and a southward shift of an upper-level westerly maximum at about 12 km (figure not shown). These features are consistent with those in the NCEP reanalysis. As a result, the mean wind shear indicated by the mean wind profiles in Figure 4c between 4 km and 10 km increases from 1 ms^{-1} in the non-nudging experiment to 3 m s^{-1} in the control experiment due to the enhanced mid-level easterly maximum. There is only a small increase in the vertical shear below 4 km. In agreement with *Dunion and Velden* [2004], Figure 4 suggests that the presence of the SAL also suppresses tropical cyclone activity by increasing the local vertical wind shear via enhanced mid-level winds.

5. Conclusions

[13] Using the new data products from the AIRS suite on the NASA's Aqua satellite, the SAL and its influence on the formation of Hurricane Isabel (2003) are investigated numerically in this study. Two numerical experiments are conducted with MM5. In one experiment, the thermodynamic effect of the SAL is better represented by relaxing the model thermodynamic state to the AIRS temperature and humidity profiles while in the other experiment the effect of the SAL is included only through the initial and boundary conditions derived from the NCEP reanalysis. By incorporating the AIRS data, the model can better simulate the large-scale flow patterns and the evolution of Hurricane Isabel in terms of the timing and location of formation and the subsequent track. It is suggested that the retrieved temperature and humidity profiles of the AIRS level 2 products are useful for investigating the influence of the SAL on tropical cyclones. The simulations suggest that SAL may have delayed the formation of Hurricane Isabel and inhibited the development of another tropical disturbance to the east. This study confirms the argument by *Dunion and Velden* [2004] that the SAL can suppress Atlantic tropical cyclone activity by increasing the vertical wind shear, reducing the mean relative humidity, and stabilizing the environment at low levels.

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